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Manipulation of Micro Scale Particles in Optical Traps Using Programmable Spatial Light Modulation

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Abstract

1064 nm light, from an Nd:YAG laser, was polarized and incident upon a programmable parallel aligned liquid crystal spatial light modulator (PAL-SLM), where it was phase modulated according to the program controlling the PAL-SLM. Light reflected from the PAL-SLM was injected into a microscope and focused. At the focus, multiple optical traps were formed in which 9.975 μm spheres were captured. The traps and the spheres were moved by changing the program of the PAL-SLM. The motion of ordered groups of micro particles was clearly demonstrated.

Introduction

As interest in nanotechnology increases, the need for developing methods for manipulating and interrogating nano structures as well as directing and monitoring nano processes has also increased. This project is a result of that need and, in part, is based on work previously done at NASA Glenn Research Center demonstrating the viability of using phase modulation and interferometry to manipulate a single particle in an optical trap¹. An optical trap, or optical tweezers, provides a method for performing nano scale operations. While optical tweezers cannot directly resolve the details of a nano structure, employing a micro scale tool to interrogate or manipulate nano structures is expected to circumvent this difficulty.

A programmable PAL-SLM provides a method for generating multiple optical traps from a single beam of light via phase modulation. By changing the control program of the PAL-SLM—and thus, the phase distribution—the number and position of optical traps can be changed, allowing spatial control of multiple particles. In this project, Microsoft PowerPoint is used to send a series of control images to the PAL-SLM since PowerPoint provides control of timing between control images. The PAL-SLM used provides 2π radians of phase modulation with 30 ms rise time and 40 ms fall time for π radians phase modulation.

Experimental Method

Control Image Construction

Control images for the PAL-SLM were generated in MATLAB by substituting a phase distribution function into the following transfer function for the PAL-SLM:

$$I = 4.10614 + 59.5342\Phi - 7.88323\Phi^2 + 0.675005\Phi^3 \quad (1)$$

The transfer function is specific to the device and it maps grey scale values (0 to 255) to the phase state at each pixel. The control image is made from a 480×480 matrix of the values from the transfer function.

Two phase functions were used. The first phase function generated a linear pattern of traps and was defined as follows:

$$\Phi(x, y) = 2\cos^{-1} \left\{ \cos \left[\pi f_{xy} (x' + y') \right] \right\} \quad (2)$$

where f_{xy} is the spatial frequency (pixels⁻¹), and x' and y' are functions of x and y in the general case. For the identity transformation, $x=x'$ and $y=y'$. The second phase function generated a diamond shaped pattern of traps and was defined by the following function:

$$\Phi(x, y) = 2\cos^{-1} \left[\left(\frac{1}{2} \right) \cos(f_x \pi x') + \left(\frac{1}{2} \right) \cos(f_y \pi y') \right] \quad (3)$$

Rotations of the images are performed by recalculating the original image with the following functions for x and y :

$$\begin{aligned} x' &= x \cos(\theta) - y \sin(\theta) \\ y' &= x \sin(\theta) + y \cos(\theta) \end{aligned} \quad (4, 5)$$

where x and y are pixel coordinates prior to the rotation and θ is the angle of rotation, in radians. Rotations were performed in $\pi/36$ increments, over 2π radians.

Optical Tweezers Construction and Conditioning

1064 nm light, from a 2 watt Nd:YAG laser (fig. 1) was expanded and injected into a polarizing cube beam splitter. P-polarized light from the beam splitter was projected upon a piezo driven, steerable mirror. S-polarized light from the beam splitter was projected onto the PAL-SLM. Light incident on the PAL-SLM was phase modulated under the control of calculated intensity patterns (eq. 1) fed to the PAL-SLM via Microsoft PowerPoint. The S and P-polarized components were recombined in another polarizing cube beam splitter, and the resulting beam was reduced in size and injected via a 45° hot mirror, into a microscope. The hot mirror was used to allow condenser light from the microscope to pass to a CCD camera while preventing reflected infrared light from the trap from passing to the camera (fig. 1).

A 40x non-immersion objective was used to focus the beams onto 9.975 μm polystyrene spheres in suspension. The trap formed by the P-polarized light was used to move particles by manual control of the piezo driven mirror to the traps formed in the S-polarized beam by the PAL-SLM.

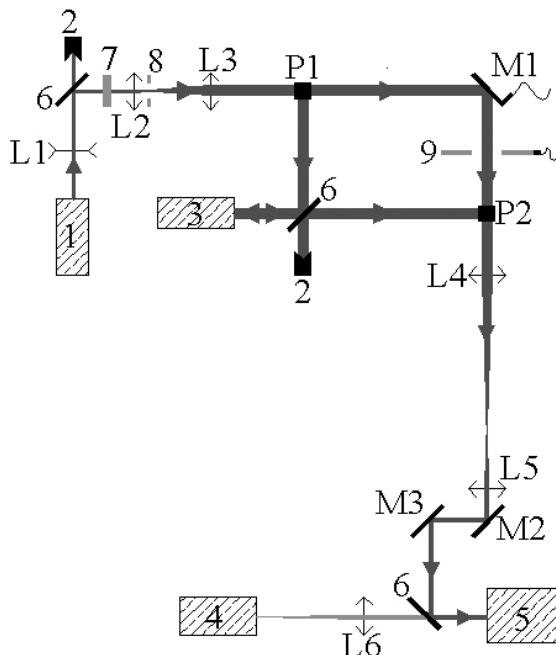


Figure 1. Experimental setup: 1. Laser; 2. Beam dump; 3. PAL-SLM; 4. CCD video; 5. Microscope; 6. Beam splitter; 7. $\lambda/2$ waveplate; 8. Spatial filter; 9. Electronic aperture; L1-L6. Lens; M1. Piezo mirror; M2, M3. Mirrors; P1, P2. Polarizing cube beam splitters.

The polystyrene spheres were contained in a well formed by sandwiching two 100 μm thick parallel strips of parafilm between a 0.17 mm thick cover slip and a microscope slide. The sphere suspension was entrained into the well via capillary action. The well was sealed with epoxy to prevent air infiltration.

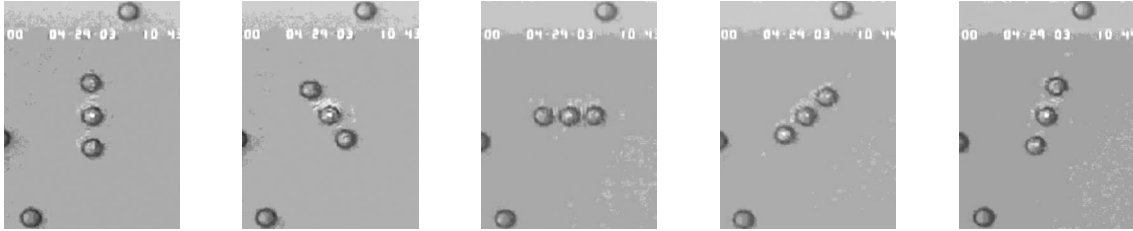
Results and Discussion

Observations were made with a 200 mW light beam of 17 mm diameter incident on the PAL-SLM (S-polarized). P-polarized light had the same diameter and a power of 420 mW. Initial tests found the traps formed to be weak. It was discovered that the laser had a divergence much greater than factory specifications: 3.6 mrad specified versus approximately 200 mrad measured. A corrective lens was inserted directly in front of the laser to correct this problem. Collimation of the beam was improved and trap strength improved significantly.

With improved collimation, the intensity distributions improved but the individual beams generated from the control images needed more spatial separation. The distance between the PAL-SLM and the first lens in the reducing telescope (fig. 1, L4) was increased. When this distance changed from 25.4 cm to 100 cm, intensity distribution structures had better definition and increased spatial separation.

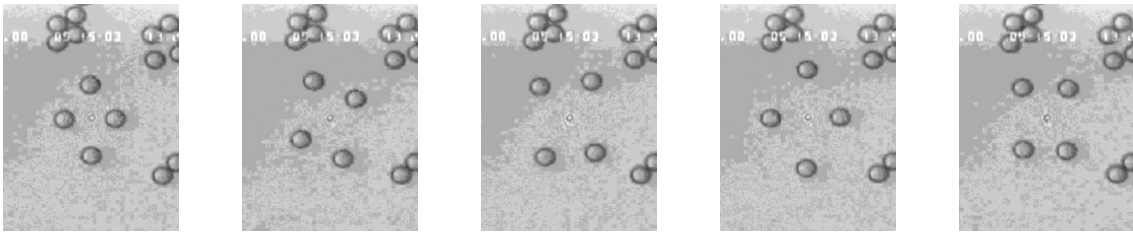
Manipulation of particles in the linear pattern of traps (eq. 2) was achieved using a spatial frequency, $f_{xy} = 0.135 \text{ pixels}^{-1}$ (figs. 2 to 6). Lower spatial frequencies, $f_{xy} < 0.104 \text{ pixels}^{-1}$, did not provide adequate spatial separation in the trapping plane. Spatial frequencies greater than $0.135 \text{ pixels}^{-1}$ resulted in stronger traps, but fewer traps

were visible compared to patterns generated at lower spatial frequencies. At a spatial frequency of $0.135 \text{ pixels}^{-1}$, traps were sufficiently strong to pull spheres in from distances of roughly 1.5 sphere diameters. Moreover, at this spatial frequency, the traps were sufficiently strong for a trapped particle to push up to 4 untrapped particles as rotations were performed on the pattern of traps.



Figures 2 – 6. *Three particles in linear pattern of traps undergoing rotational transformation.*

Manipulation of particles in the diamond shaped pattern of traps (eq. 3) was achieved using spatial frequencies, $0.042 \leq f_x, f_y \leq 0.060 \text{ pixels}^{-1}$. Several combinations of linear translations and rotations were performed (figs. 7 to 11). At spatial frequencies, $0.042 \leq f_x, f_y \leq 0.051 \text{ pixels}^{-1}$, traps were strong with no noticeable difference in trap strength in that spatial frequency range. However, with spatial frequencies, $f_x, f_y = 0.060 \text{ pixels}^{-1}$, it was observed that with each rotational increment, the trapped spheres moved more slowly to re-center in their respective traps.



Figures 7 – 11. *Four particles in diamond shaped pattern of traps undergoing rotation and linear translation.*

As the intensity distributions were rotated, rotations were limited to increments of $\pi/36$ radians. Limiting rotation to this increment was done because greater increments required longer image duration since the time for the sphere to fall back to the center of the trap would be increased.

In both the linear pattern and the diamond pattern, it was observed that traps located in or passing through the lower half of the field of view (figs. 2 to 11) were not as strong as traps in the upper half of the field of view. Alignment of optical components in the experimental setup was optimized, improving trapping strength in the lower half of the field of view, but this did not completely resolve the problem. Cleaning optical components produced no noticeable change.

A source for this asymmetric—with respect to the viewing plane—trapping force was considered. Control images were transmitted to the PAL-SLM via a VGA port on

the computer on which they were stored. As a result, control images were a function of the pixel aspect ratio of the computer display. The computer display resolution was set to 640×480 ppi, matching the resolution of the PAL-SLM; however, the PAL-SLM has square pixels. The nature of how the calculated control image was transformed as a result of differing pixel aspect ratios between the computer display and the PAL-SLM was not quantified.

Concluding Remarks

This project satisfactorily demonstrated the viability of using a PAL-SLM in the infrared to manipulate multiple micro scale particles simultaneously.

References

1. R. Seibel, "*Manipulation of Micro Scale Particles in an Optical Trap Using Interferometry.*" NASA/CR—2002-211975 (2002).
2. J.W. Goodman, *Introduction to Fourier Optics*, 2nd ed. (McGraw Hill, New York, 1996).
3. Y. Kobayashi, Y. Igasaki, N. Yoshida, N. Fukuchi, H. Toyoda, T. Hara, and M.H. Wu, "*Compact High-efficiency Electrically-addressable Phase-only Spatial Light Modulator.*" SPIE Proceedings Series 3951 (2000): 158–165.
4. T. Poon and P.P. Banerjee, *Contemporary Optical Image Processing with MATLAB*. (Elsevier Science, New York, 2001)
5. A.J. Decker, "*Interferometer control of optical tweezers.*" SPIE Proceedings Series 4778 (2002): 142–149.

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